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Technical Memorandum

Lightning Protection of Wind Turbines with Special Consideration of VAWTS

J.G. Keller

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WITH SPECIAL CONSIDERATION OF VAWTS

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SUMMARY

Wind turbines, like all tall structures, are natural conductors for lightning strikes. This, coupled with the fact that high wind regions are sometimes linked with high thunderstorm occurrences (e.g., prairie regions in Canada) makes lightning protection of wind turbines an essential part of any installation, for the safety of both equipment and personnel.

This paper discusses the areas of concern in the lightning protection of wind turbine equipment, with special emphasis on instrumentation and control signals. Also discussed are safety aspects with respect to operating personnel as well as others who may walk around a site. The step potential phenomenon around a lightning strike is a very significant hazard not only to people but also to most living things.

With careful design and choice of components a wind energy conversion system (WECS) can be made safe and reliable even if it is situated in a high lightning occurrence area. To achieve this, the design engineer must ensure that the structure is well grounded and signals are protected or isolated before interfacing with the turbine controller or data acquisition system.

RÉSUMÉ

Comme toutes les structures élevées, les éoliennes constituent des conducteurs naturels pour la foudre. Considérant ce facteur et le fait que les régions où soufflent des vents forts sont quelquefois exposées à des orages violents (par exemple les Prairies canadiennes), il est essentiel qu'un dispositif de protection contre la foudre sont intégré à toute éolienne, afin d'assurer tant la sûreté du matériel que la sécurité du personnel.

La présente communication porte sur les problèmes que pose la protection contre la foudre du matériel éolien; l'accent est mis particulièrement sur les instruments et les signaux de commande. Elle traite aussi de la sécurité du personnel d'exploitation et des autres personnes pouvant se trouver à proximité. Le phénomène de potentiel en échelons qui accompagne la foudre présente un grand danger pour les humains et pour presque toutes les formes de vie.

Lorsque les éléments sont bien conçus et choisis, un système de conversion de l'énergie éolienne (SCEE) peut être sans danger et faible même dans une zone souvent touchée par la foudre. Pour réaliser ces conditions, l'ingénieur d'études doit s'assurer que la structure est bien mise à la masse et que les signaux sont protégés ou isolés avant d'arriver au régulateur de la turbine ou au système d'acquisition des données.

LIGHTNING PROTECTION OF WIND TURBINES WITH SPECIAL CONSIDERATION OF VAWTS

J.G. Keller

1.0 INTRODUCTION

The design effort required for lightning protection of a wind turbine is based on the following considerations:

1. the safety of personnel at the site; this is a high priority
2. the potential damage and cost incurred by a lightning strike
3. the thunderstorm days per year (isokeraunic level) at the site

An example of a low priority or minimum protection case is that of a site in a remote area having a "low thunderstorm day" rating (i.e., low isokeraunic rating). The machine would operate in "automatic mode" with no permanent personnel at the site. The Christopher Point installation is a good example of this. This turbine is situated on a remote site on Vancouver Island, British Columbia, in an area having an isokeraunic level less than 5. A person is present at the site only for an hour or two every month and the machine is not instrumented. For this type of installation an absolute minimum need be spent on lightning protection.

However, the 500 kW machine (Project Aquilo) at the Atlantic Wind Test Site on Prince Edward Island is quite a different case. The machine is in a frequently visited area. During the summer months over 3000 visitors have had full access to the site. The machine is highly instrumented with strain gauges and other sensors connected into a very expensive data acquisition system. Lightning, although relatively uncommon, still occurs. For this type of installation it is essential to protect personnel, the machine, and the data acquisition system.

In fact, following are the three main areas of lightning protection:

1. protection of personnel/equipment from a step potential due to the lightning strike

2. protection of measurement devices, control sensors, and data acquisition system (i.e., anemometers, tachometers, microswitches, strain gauges, computer, microprocessors, etc.)

3. protection of the machine (i.e., bearings, generator, electrical system)

2.0 LIGHTNING CHARACTERISTICS

For proper design of equipment and protection systems certain characteristics of lightning strikes and the strike frequency must be known.

The following parameters and the typical range of values are used to characterize a lightning strike (1-4).

1. Stroke Charge content is of the order of about 2 to 20 C.

2. Peak Stroke Currents vary between 1000 and 400 000 A. The majority of strokes range from 5 to 50 kA with 20 kA being a typical peak current. Current peaks exceeding 80 kA are rare.

3. Following Current Flow Durations vary from about 10 to 10^3 μs.

4. Current Rise Times vary from less than 1 μs to more than 10 μs (4 μs typical).

5. Rate of Current Rise typically ranges from 5.5 to 30 kA/μs.

6. Field Recovery or recharge time requires about 10 s field recovery time before another stroke is possible.

7. Average Field Strength under a storm is between 10 and 30 kV/m. It rises to between 300 and 500 kV/m just before a strike. Field strength is potential voltage per unit length between the cloud and ground during a storm.

8. Cloud-to-Earth Potential is estimated to exceed 100×10^6 V within an active storm area.

From the above data it can be easily seen that a lightning strike has the potential to cause severe damage at a wind turbine site.

Potential rises in the immediate area of the strike can cause secondary flash-overs between objects or from the ground to other structures. Lethal currents can travel great distances down wire fences or instrumentation wires. This all has to be taken into account when the protection system is designed.

A simulated lightning strike current profile used for testing effects of lightning strikes on equipment is illustrated in Figure 1.

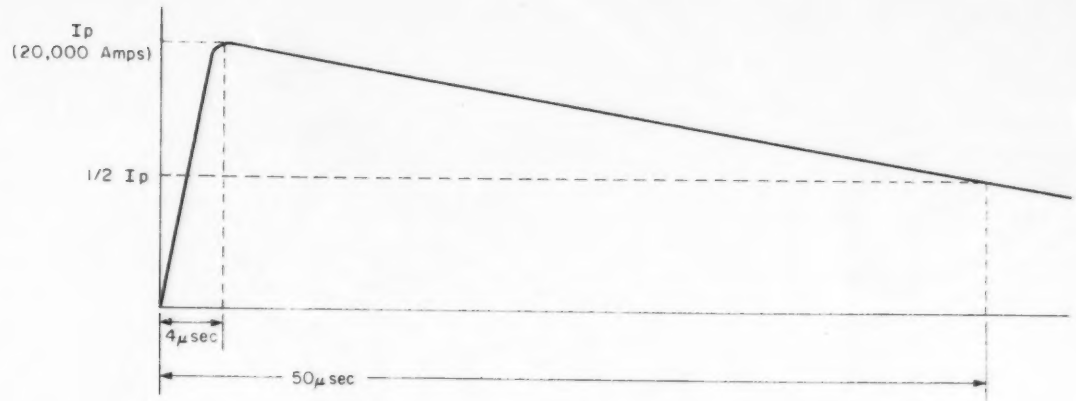

Fig. 1. Current profile of typical lightning strike

The extremely high current rise frontal during a lightning stroke induces high voltage on lines not carrying the actual current. Thus, even if the stroke follows a good ground conductor, adjacent control or instrumentation lines may have induced voltages reaching thousands of volts. The potential induced will be a function of the circuit impedance, the distance from the conducting wire, and the rate of current rise. Current drive circuits and voltage limited circuits have a much better chance of surviving this type of phenomenum.

3.0 THUNDERSTORM DAYS

A thunderstorm day is defined as "an observational day during which thunder is heard at the meteorogical station; precipitation need not occur."[1] Figure 2 shows the thunderstorm days for Canada (5).

The probability of a strike to an object is related to the ground flash density at the site. Ground flash density is the average number of lightning strikes to earth for a given area and time period. This quantity is usually expressed in number of flashes per square kilometre per year. Unfortunately, few data of ground flash occurrences are available. The ground-flash density can be estimated using the isokauronic level for a region. The estimated ground flash density can be translated into "probability of a strike" to a structure as a function of structure height. Caution on using these approximations should be observed since the isokauronic level does not distinguish between the cloud-to-cloud and the cloud-to-ground flashes, nor does it account for storm duration, the number of storms in one day, or the local terrain, all of which can affect the

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[1] McGraw - Hill: Dictionary of Scientific and Technical Terms

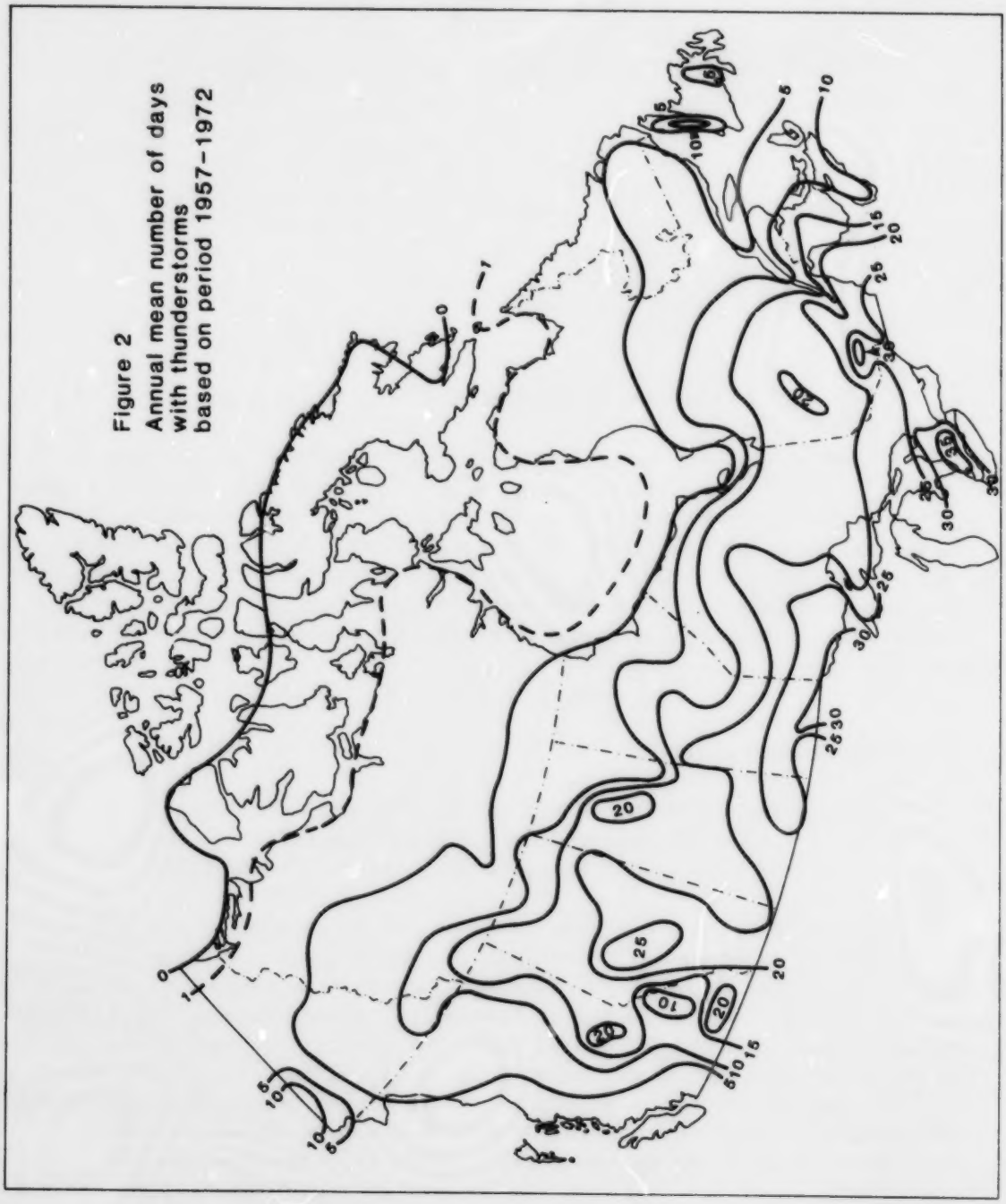

Figure 2
Annual mean number of days with thunderstorms based on period 1957–1972

probability of a strike. Methods of estimating the ground flash density from the isokauronic level vary widely depending on the researcher and the data obtained. For example, in an isokauronic area of 10 the ground flash density has been estimated to be somewhere between 0.5 and 2.0 flashes per square kilometre per year. To further complicate matters, the relationship between ground flash density and the probability of a strike as a function of structure height is also very much unknown. While most researchers agree that it is dependent on the area that the structure shields, the actual calculation is at best an approximation since it depends on several variables ranging from structure grounding to local topography, soil, and ground water conditions.

To vastly simplify the calculations of probable strikes per year the author has used a linear approximation (6-8). This approximation states an 85 m (275 ft) structure standing in an isokauronic area of 30 thunderstorm days a year will probably be hit about once a year. Thus,

[1] $$P_H = T_D h/2550$$

where

P_H = probability of a hit per year
T_D = thunderstorm day
h = height of structure

Figure 3 illustrates the family of curves represented by equation [1]. These curves are valid for structures under 100 m and are conservative compared to other calculations, i.e., the results will usually indicate a higher number of strikes than other methods. The results from these other methods are as low as one fifth that of equation [1].

Using the above information, the probable number of lightning strikes on the Aquilo machine can be calculated. The machine is about 40 m high. From the isokauronic map, North P.E.I. is located in a zone of about 15 thunderstorm days per year. Using the curves from Figure 3, Aquilo would be hit about 2½ times in 10 years. If there was a wind farm on the same site consisting of 10 similar machines, the probability would be 1½ strikes per year. This, of course, is a simplified calculation. In reality the number of strikes could be slightly higher due to the guy cables, which provide a larger target area for the lightning.

The above calculation technique has been confirmed for the 50 kW VAWT at Swift Current, Saskatchewan. The structure is 25 m in height. The isokauronic zone there is 25 thunderstorm days per year. From the curves

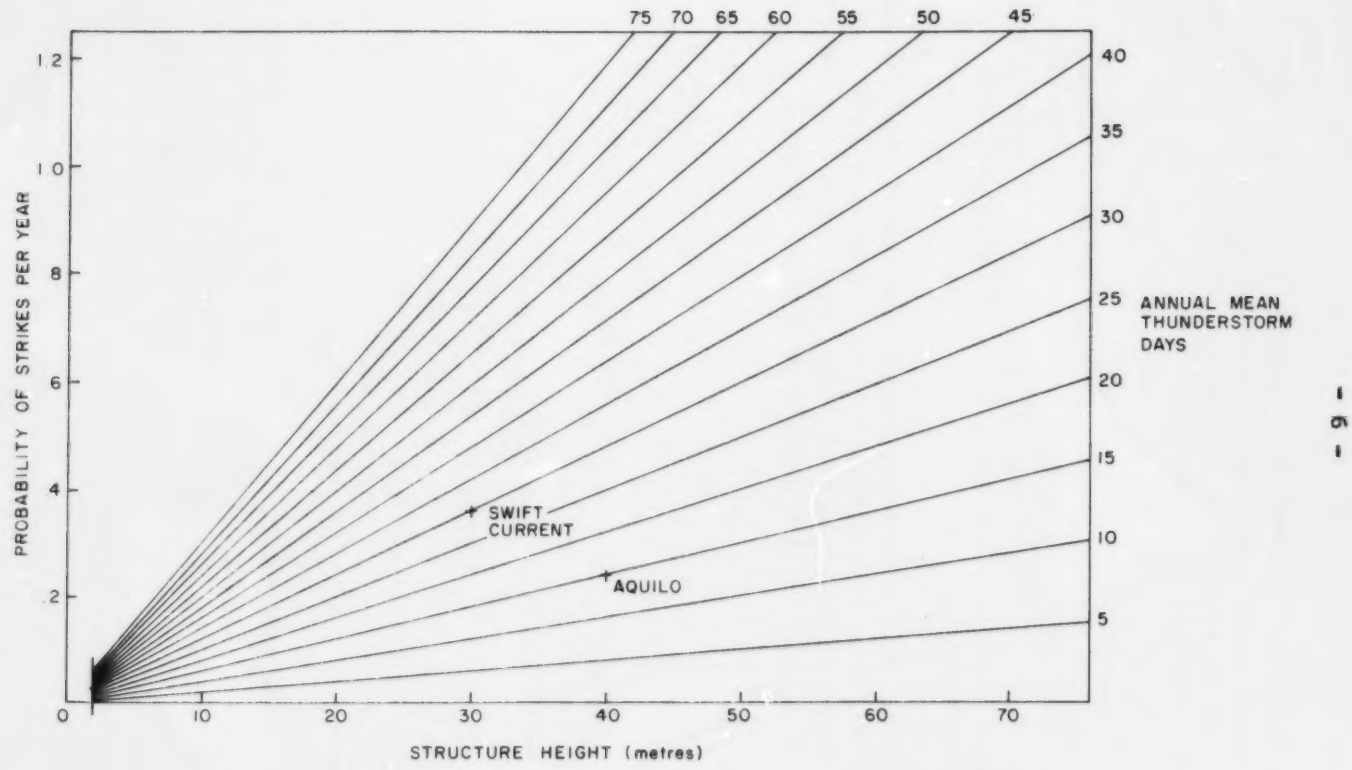

FIGURE 3: RELATIONSHIP ISOKERAUNIC LEVEL, STRUCTURE HEIGHT, AND PROBABILITY OF LIGHTNING HITS PER YEAR

in Figure 3 the machine probably would be hit once every 3 years. The machine has been struck at least once during its four years of operation, thus giving some verification to the prediction.

4.0 PROTECTION OF THE MACHINE

A sketch of a typical 500 kW VAWT (Aquilo) is shown in Figure 4. If lightning strikes the machine at its highest point, large currents will flow down to ground as illustrated by the arrows. The guy anchors for this machine are steel I-beams embedded in concrete. The 8 in. I-beam extends about 16 ft through the soil before entering the concrete foundation. The I-beam surface is bare galvanized metal, which provides an excellent path to ground. The power module at the base of the machine is well grounded with a heavy gauge copper coil buried below the foundation. This ground coil is connected to the steel structure of the module, as well as to the generator cases and switch gear enclosures, using heavy gauge copper wire. During a strike, lightning currents will tend to flow down the three pairs of guy wires to earth and also down the rotor column to the power module ground.

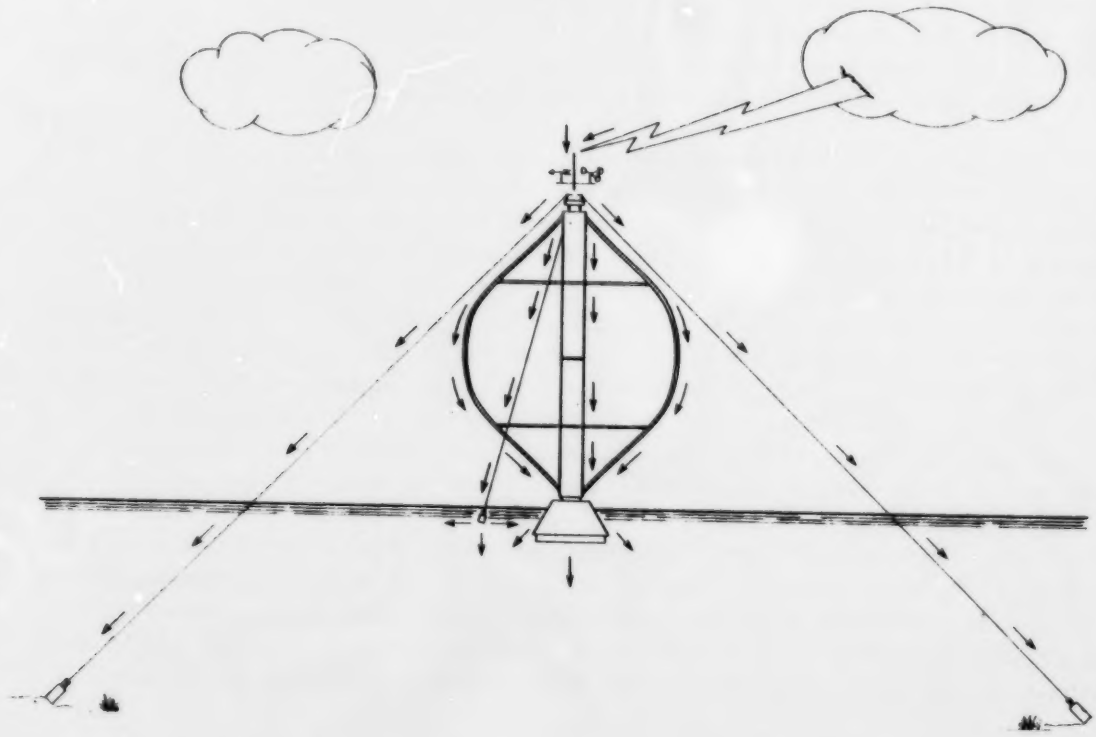

Fig. 4. Paths of lightning current

Critical areas of the machine that require protection are the bearings on the lower and upper ends of the rotor and the electrical apparatus. The DAF Indal 500 kW machine uses journal type bearings at both the upper and lower ends of the rotor. Very little is known about the effects and potential damage from lightning strikes on this type of bearing. The consensus,[2] however, is that they probably are less prone to catastrophic damage than rolling element steel bearings. The rotor when operating is actually "floating" on an oil film which has a very high electrical resistance. This would tend to direct most of the current from the strike down the guy wires. Brushes have been proposed on the top and bottom section of the rotor to bypass any electrical discharge away from both the instrumentation wiring and the bearings. This is recommended on this type of machine to reduce the risk of lightning discharge damage. The DAF Indal 50 kW machines have such brushes installed.

Other types of damage that may occur when lightning strikes a turbine are from the large impulse currents that flow throughout the structure during a strike. Down conductors should be installed without sharp corners and should be secured at frequent intervals. Electromagnetic forces between conductors can be extremely high. This also holds true for the structure and the mechanical parts that are not designed to carry such currents. With a current of 20 000 A, forces between parallel conductors 0.1 m (4 in.) apart are around 800 N/m (55 lb/ft). Because of this, care has to be taken that all cables are tied down adequately.

The blades on most VAWTS are virtually immune to damage even from a direct hit, since they are normally constructed of extruded aluminum, which is an excellent conductor. There have been no known reports of lightning damage to extruded aluminum blades. The amount of metal and overall size provides an excellent path for lightning currents. There would be a serious problem, however, if the blades were constructed of non-conducting material such as fibreglass. In this case it is advisable to imbed a wire mesh which is well grounded just below the blade surface or to cover the blade with a metallic material which can conduct any lightning current. There have been several reports of damage to non-metallic blades from lightning. The Swedish horizonal axis turbine at Maglarp has suffered damage to both the metallic covering on the blade leading edge and to strain gauges imbedded into the fibreglass. The Swedes reported that the fibreglass blades received several strikes. Instrumentation cables, which run inside the blade material, unfortunately provided ideal paths for the lightning current. This caused minor pitting in the fibreglass blade when strain gauges were vaporized by the high currents. Foil covering the

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[2] Note: This conclusion follows various discussions with experts at NRC, Division of Electrical Engineering, and DAF Indal.

leading edge was also vaporized in small areas where direct hits occurred. Concensus is (see ref. 9) that blades either should be totally of insulative material or highly conductive. The Swedes concluded that on future machines instrumentation cables would not be run in the fibreglass blades and a more comprehensive protection would be employed. This might involve a heavy screen combined with conductors of adequate size to carry the lightning currents, thus rendering the blades highly conductive.

Since Aquilo has extruded aluminum blades, no protection on the blades against lightning strikes was required. Power lines to the machine have been protected using standard techniques employed by the utility (buried cable where possible and the main transformers and lines protected with overhead ground wires and lightning arresters). In conclusion, the main requirements to protect a machine such as Aquilo would be to

1. provide good solid grounds for the base and anchors

2. add brushes to by-pass current around the upper and lower rotor bearings

3. ground all switch gear, control cabinets, and generator housings by heavy gauge copper cable

4. use lightning arresters and overhead ground wires to protect power transformers and lines.

5.0 PROTECTION OF THE INSTRUMENTATION AND CONTROLS

The protection of instrumentation is probably the most difficult part of lightning protection because sensors tend to be very sensitive to high voltage/current surges and experimental turbines tend to have extensive sensor wiring on them. The following paragraphs illustrate how to minimize the damage, while realizing that some sensors may be lost if there is a direct strike.

5.1 Cone of Protection

Anemometers and other meteorological sensors which may be situated on top of the machine or on separate towers can be protected easily by lightning rods protruding above the sensor to absorb any direct strikes. Figure 5 illustrates this method of protection. The rule of thumb indicates that if the angle θ is 30° the chance of an object under the "cone of protection" being directly hit is greatly reduced by a factor of several hundred. This factor reduces significantly as the height of the cone exceeds 45 m. This is due to an increase in the possibility of direct

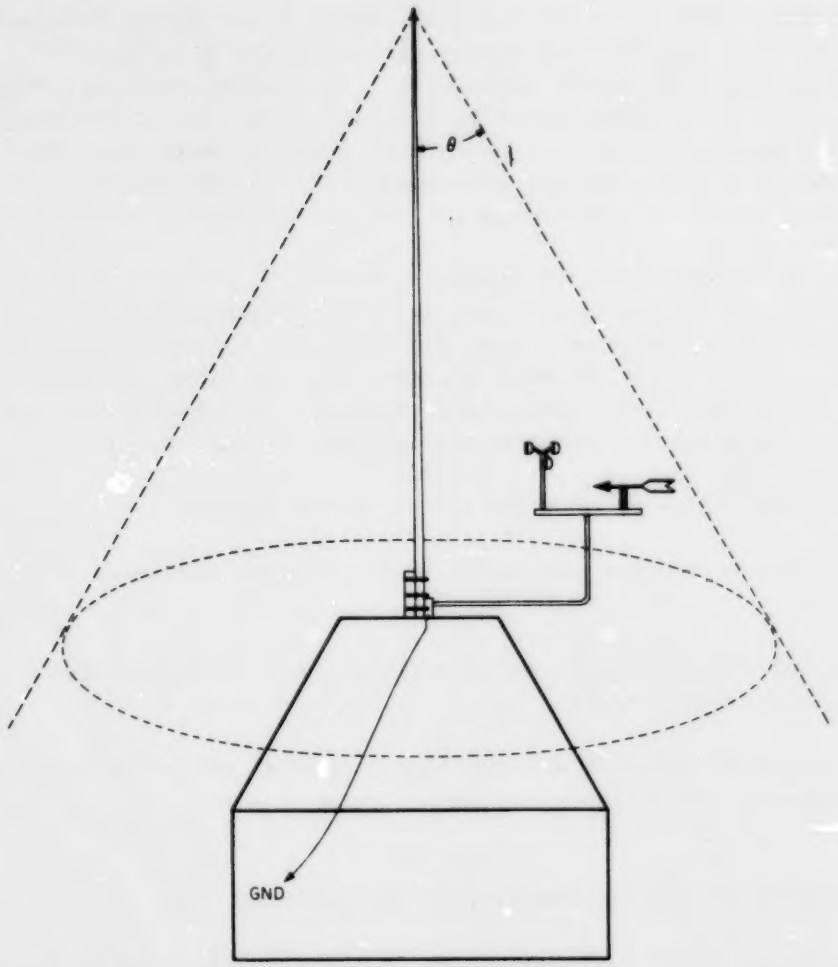


Fig. 5. Lightning protection: cone of protection

hits coming in from the side. Thus, as in Aquilo, where the machine has been calculated to be hit roughly once every 4 years, the top anemometer, if placed under such a cone, would have a chance of receiving a direct hit reduced to once in several hundred years. The lightning rod has to be well grounded or side-flashes are still a possibility. This rule of thumb also applies to other sensors and/or buildings needing protection. Running a protective "tent" is also possible for buildings or large areas requiring protection by stringing a heavy conductor above the area, as shown in Figure 6.

While the 30° angle is widely accepted as an ultimate protection in high isokeraunic areas, a larger angle of 45° is often adequate.

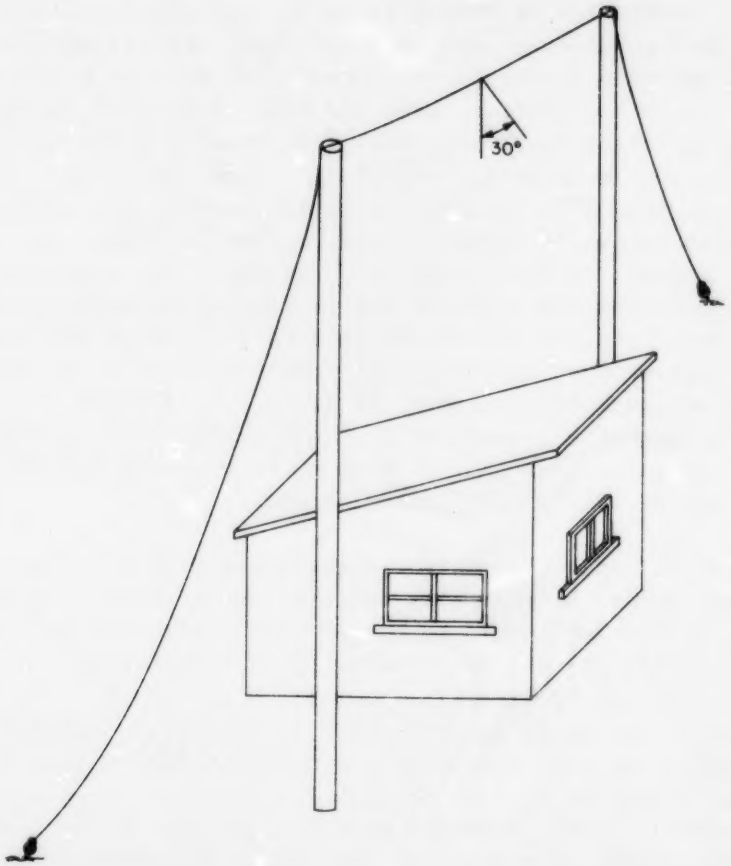


Fig. 6. Lightning protection: overhead ground wire

5.2 Circuitry and Sensor Protection

While in most cases there is a very limited selection in the type of sensor one can choose, it is beneficial to realize that some sensors can withstand voltage or current surges better than others. Anemometer heads which employ little, if any, electronics appear to have a better reliability with respect to lightning survival. Circuits which measure frequency can be designed to withstand large voltage surges by employing gas discharge varistor, voltage limiting protection circuits, or optical isolation techniques without causing any reduction in the accuracy of the readings.

The most difficult decision with respect to instrumentation is at what location in the circuit does one implement the protection. This often depends on the importance and type of the signal (i.e., control or

measurement). Protection is essential before signals are introduced into an expensive data acquisition system. Low level signals such as from strain gauges are very difficult to protect. Usually in the case of low level signals plug-in amplifier cards are used to amplify the signals first. These amplifier cards are usually located as close to the sensors as possible and should be easily replacable since they will be damaged in the case of a strike. The amplified signals are then protected by standard barrier circuits (shown in Figure 7) before they continue into measurement electronics, control, or data aquisition systems. It is essential that once signals have been subjected to the protection circuitry, they are removed from other unprotected wiring as this would void the protection. It is also important that all electronics are enclosed in grounded metal boxes to help shield them from both the lightning currents and the resulting EMI (Electromagnetic Interference). All sensor cabling should be twisted shielded pairs, not only to keep noise at a minimum but also to help protect the circuitry from lightning EMI.

Signals which enter the control electronics from long distances (such as anemometers) should be optically isolated using standard chips or fibre-optic cable. All cables should be buried rather than strung overhead. Again, frequency translators which allow optical isolation techniques are ideal for this sort of application. Control circuits which involve simple on/off, run/stop, or timing functions can be optically isolated before entering sensitive microprocessor or other controllers. Standard one-chip packages are now available which convert low level voltages directly to fibreoptic signals. Other standard packages convert the fibreoptic signal back to digital or analog electrical signals with extreme accuracy. Fibre-optic lines are immune to both noise pick-up and damage by lightning strikes (although heating of adjacent metal which has been struck has been known to cause damage to the fibreoptic cable). Figure 8 shows some of the more common techniques for optical isolation. Current transmitters are generally quite rugged and are constructed to withstand reasonable voltage surges. Voltage output circuits are usually sensitive to high voltage surges but they have the advantage of easily installing surge protection circuits as shown in Figure 7. The device shown is a typical protection circuit against high voltage faults on instrumentation lines.

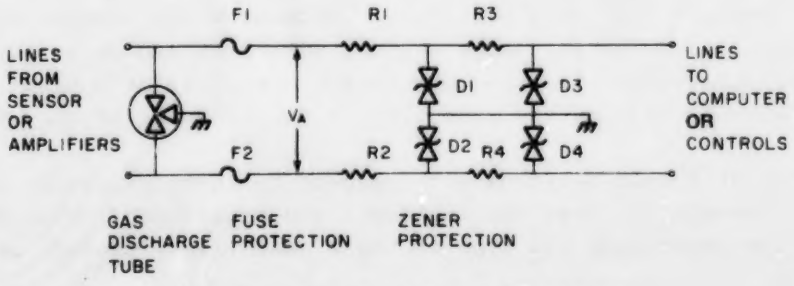
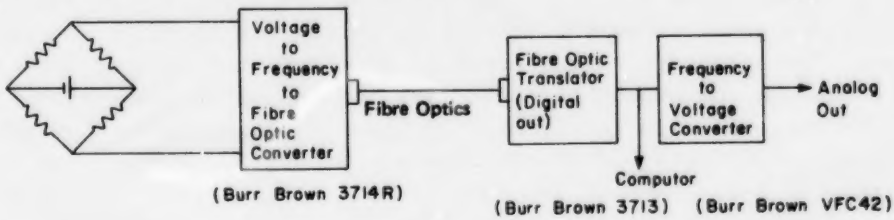
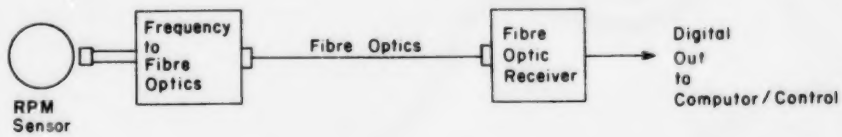


Fig. 7. Standard barrier circuit

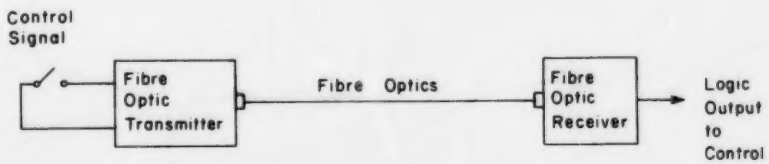
The gas discharge tube provides a long-term discharge path for any high voltage present on the line. The zener diodes provide both a short-term discharge for high voltage on the line and long-term voltage limiting for lower voltages (< 90 volts) if the input impedance of the measuring device is greater than 1 megohm the resulting error due to resistor voltage drop is small. However, diode leakage can be a problem if the signal is either low level or high impedance. High impedance circuits are very difficult to protect without introducing error into the signal and have to be buffered before protection can be used.



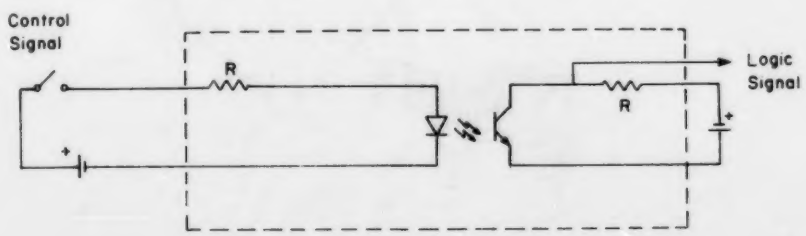
a) - STRAIN BRIDGE SIGNAL OPTICALLY ISOLATED AND TRANSMITTED VIA FIBRE OPTIC LINK



b) RPM SENSOR SIGNAL TRANSMITTED VIA FIBRE OPTICS



c) CONTROL SIGNAL TRANSMITTED VIA FIBRE OPTICS



d) CONTROL SIGNAL ISOLATED VIA OPTICAL ISOLATOR

Fig. 8. Optical isolation techniques

6.0 GROUND GRADIENT PROTECTION

It is well known by farmers that cattle have a habit of gathering under an isolated tree during thunderstorms. If the tree is struck by lightning, often several animals, if not all, are killed. This occurs even though few are directly hit by the stroke or any of the side flashes. The majority are electrocuted by the voltage gradient at the ground surface around the tree. This voltage is caused by the lightning current. In high resistive soil an animal can be quite some distance from the tree and still receive a lethal shock. Figure 9 illustrates how a cow may be killed due to voltage gradient. When the turbine is struck the lightning current flows down the structure to the ground. From here the current spreads out radially through the ground to neutralize the charge in the earth. Since the ground resistance is fairly high and the lightning current is quite substantial, high voltage differentials are produced. The circles dotted around the imaginary turbine are equipotential lines. The illustration assumes the ground composition is uniform and of equal resistance; in reality these equipotential lines may be distorted due to local ground conditions. The cow in this case has a voltage potential E_g impressed between

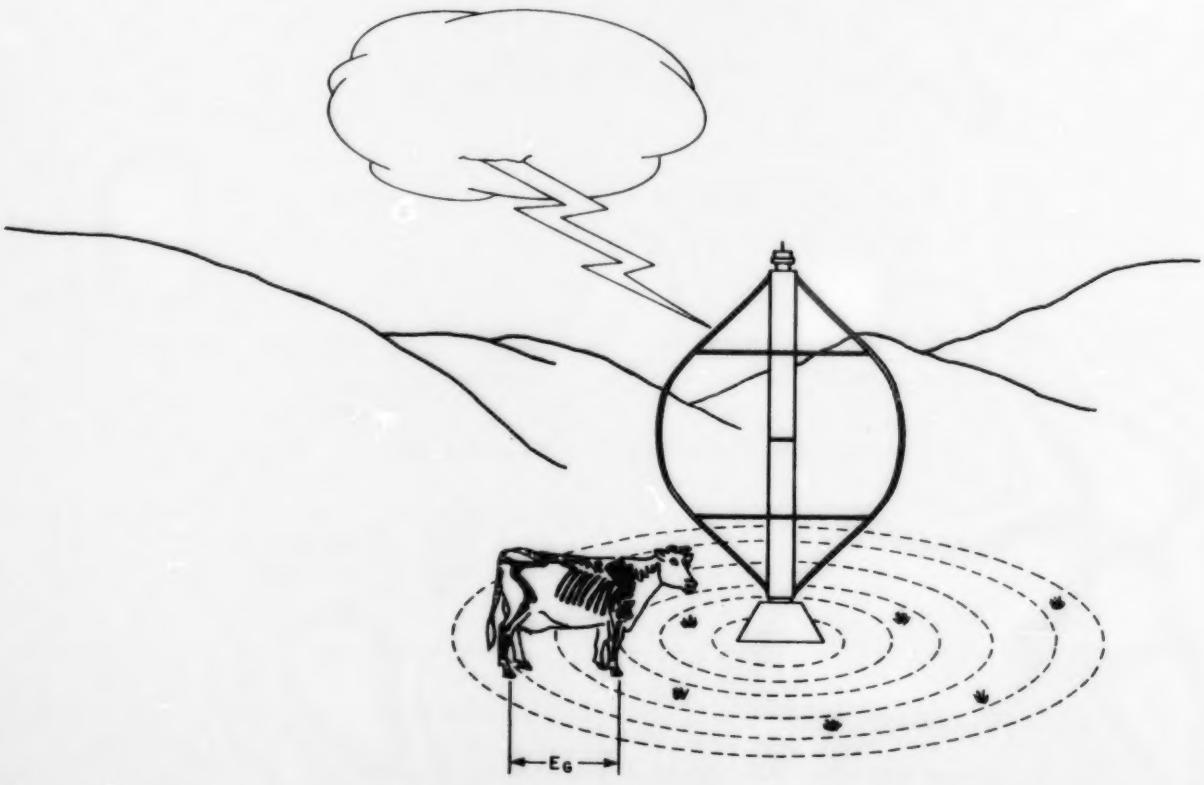


Fig. 9. Ground potential kills a cow

her hind and fore legs. This potential can be extremely high, reaching 150 kV/m near the turbine. Thus our cow may have up to 200 kV between her front and back hoofs. A huge current will flow through her, possibly causing death. Golfers and other people outdoors have been seriously injured or killed by the same phenomena. There are a few solutions to this problem; some are more practical than others. One solution would be to teach cattle either to stay away from trees and other tall objects or stand on one hoof during lightning storms. This, of course, is rather a ridiculous notion (although people might be advised that running always keeps only one foot on the ground). A more practical solution is to somehow

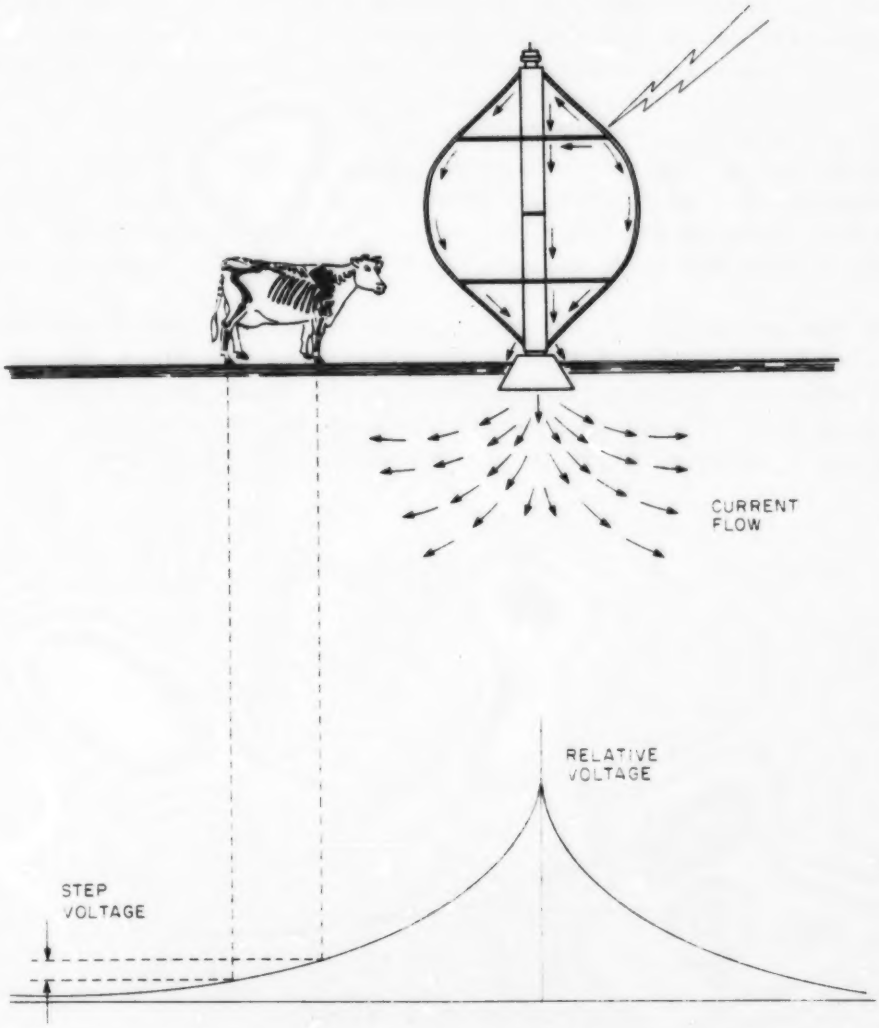


Fig. 10. Ground current flow and relative ground potential near lightning strike

reduce the ground gradient during a strike. This gradient potential is quite dependent on the ground resistance and ability of the local area to absorb the lightning charge. As the distance from the stroke increases the area available to the current increases rapidly, thus the ground gradient voltage reduces significantly. Figure 10 illustrates this. Again a cow is shown along with the voltage potential when the lightning current has peaked. The step voltage is proportional to the resistivity of the soil and has been found to decay more rapidly than the inverse proportion with the distance from the earth electrode (due to the fact current is flowing downward as well as outward).

Thus, by reducing the soil resistance close to the object struck the ground potential can be reduced significantly. This is accomplished by burying wires running radially from the turbine connected by ring electrodes. This almost eliminates ground gradients within the ring electrode and reduces the gradients to safe levels beyond the electrode. Figure 11 illustrates this gradient reduction with ring electrode diameter. Also illustrated is the fact that surface gradients can be reduced significantly by burying a copper cable below the surface to direct more current downward, thus reducing surface current and therefore the voltage gradients.

For the protection of the Aquilo site against ground gradients a rather large ground mat was laid out. Copper wire was buried approximately 25-50 cm below the surface, interconnecting the three guy anchors and the module structure. Figure 12 shows the general layout of the Aquilo grounding. Ground rods were driven in at intervals along the cables to provide

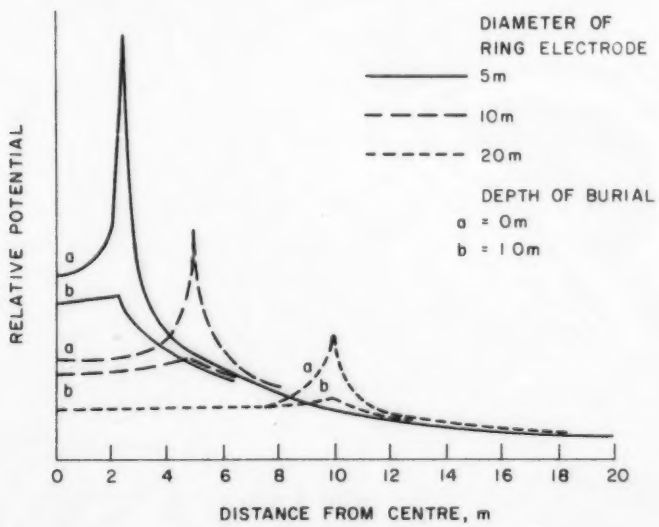


Fig. 11. Potential distribution within and outside ring electrodes of different diameter and depth of burial (Koch, 1955)

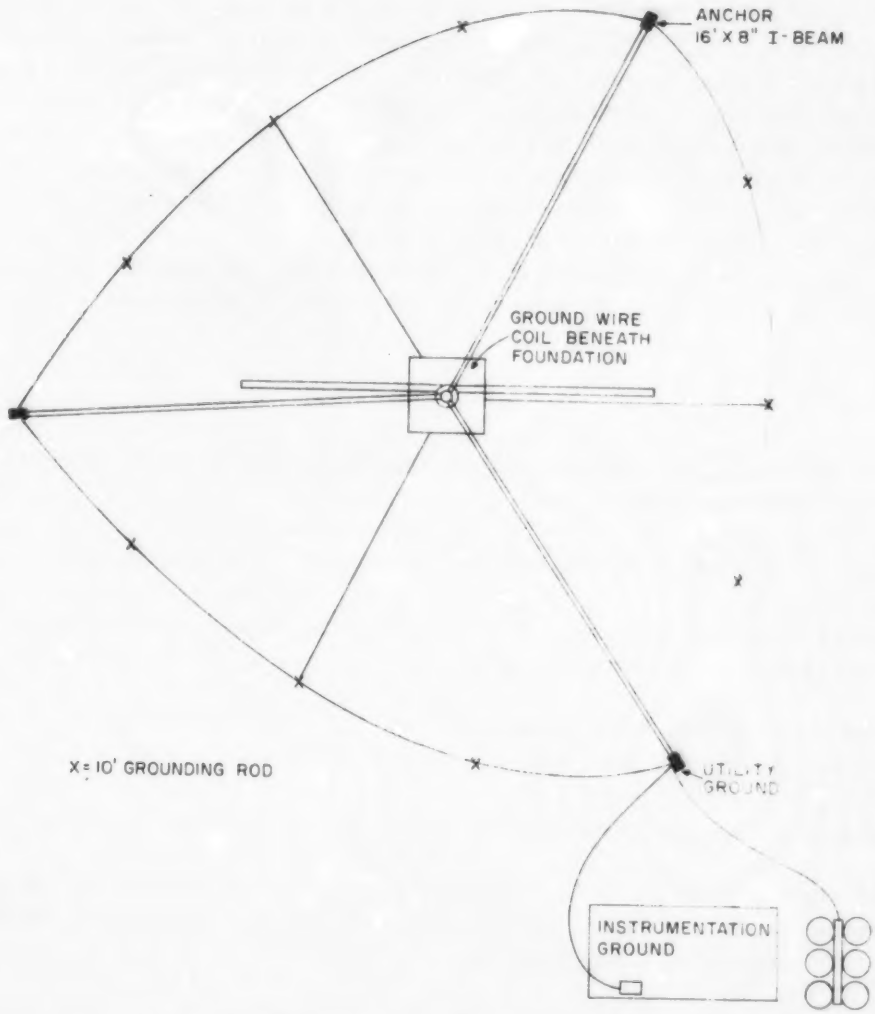


Fig. 12. Grounding system for Aquilo site

extra grounding. The anchors themselves are extremely good grounds. This system ensures that the area around the turbine is at a reasonable equipotential even during a severe lightning strike. Gradients beyond the protected area are likely to be low enough that damage or injury potential is minimal.

7.0 CONCLUSIONS

Wind turbines, like any other outdoor structures, require protection against lightning strikes. This protection has to be embodied in the fundamental design of the machine and requires care and foresight. The

over-all level of protection provided is based on consideration of safety, probability of a lightning strike, cost, and potential damage that could x occur and be tolerated. Control systems, relays, and switchgear have to be designed to withstand not only power surges from lightning strikes to power lines nearby but also direct strikes to the turbine structure. Optical isolation and voltage limiters are the best method of protection for instrumentation and data acquisition equipment. Good grounding is the most important aspect of overall lightning protection. Methods of reducing ground voltage gradients can also be employed both to improve the grounding and to reduce the chances of injury to personnel working near a machine.

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